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MEETING PAPER

San Antonio, TX; October 23-24, 1995

A Predictive Model for Pressurization of SPR Caverns

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ABSTRACT

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* Work supported by U.S. Department of Energy, Contract No. DE-AC04-94AL85000.

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Introduction

The United States Department of Energy Strategic Petroleum Reserve is currently storing over 500 million barrels of crude oil in 62 caverns which were solution mined in salt domes along the Gulf Coast. These caverns were primarily constructed in the early 1980's, although some were already in existence at the time the SPR was created. One of the concerns in operating such a large number of aging caverns is the possibility of a leak developing in one of the caverns.

Cavern leaks are often difficult to detect because cavern pressure changes occur as a result of salt creep, the geothermal heating of the oil, and the potential dissolution of salt if unsaturated brine was recently injected. In the absence of a model to predict cavern pressurization, the effects of a leak may not be discernible from the other mechanisms that influence cavern pressure.

To certify cavern integrity, the current practice involves performing a pressure test every five years (Goin, 1983). In these tests, the cavern wellbores are pressurized with nitrogen. The nitrogen level is forced to slightly below the casing seat and the nitrogen temperature and pressure along with its interface level are used to calculate any leakage over the duration of the test. This procedure has several disadvantages. The first disadvantage is that the cavern wells are only tested for leaks every five years. In the interim, a leak could go undetected. A second disadvantage is that the procedure tests for leaks in the wellbore and casing seat only. The integrity of the salt surrounding the cavern is not tested. The third disadvantage is the risk in damaging the well during the test. Nitrogen test pressures are significantly higher than operating pressures at the well head and can approach lithostatic pressure at the casing seat.

An alternative approach to leak detection is to use historical cavern pressure data, collected during a period when the cavern is not leaking, and develop a model for cavern pressurization. The model could then predict future pressures and the cavern operator could compare them with the actual well head pressures measured. The required data are simple to collect and, for SPR, are already collected. Unexplained pressure decreases, measured over periods of weeks or months, would indicate a leak somewhere in the system, either from the cavern itself or from the access wells. This would prompt the cavern engineer to check for sources of possible leakage. The alternative approach tests the entire system for leaks, not just the access wells, and it can detect leaks much sooner than periodic nitrogen testing.

To implement this procedure, all of the factors which influence cavern pressure must be accounted for in a model. The most important factors are the known oil and brine movements into and out of the cavern, the steady state and transient creep closure of the cavern, and the thermal expansion of the oil and brine in the cavern as the temperatures equilibrate with the geothermal gradient. Dissolution effects are short-term (Ostensen, 1995a) and are not included in the present model.

To investigate the possibility of implementing a cavern leak detection procedure, based on pressure monitoring of the well head, a model for cavern pressure has been developed which accounts for the above factors. There are a number of parameters in the model that can vary from cavern to cavern and are known with varying degrees of certainty. The approach, which has been adopted, is to develop a set of model parameters for each cavern. For those parameters which are reasonably well known, the parameter value is specified. Those parameters which are less well known have been determined by a nonlinear, least-squares optimization procedure which selects a value for the parameter that results in the best match between the predicted and historical cavern pressure data.

To make it possible for site cavern engineers to easily run the model, it has been implemented using Microsoft Excel. There is a different spreadsheet for each cavern, into which the model and all the optimized parameters have been preloaded. All the cavern engineer has to do is enter the daily cavern pressure readings and associated comments, and run the model. Predicted cavern pressures are compared to measured data in both tabular and graphical form.

In the remainder of this report, the creep and geothermal heating models and the optimization scheme that was used to determine the model parameters for each cavern will be described. Best-fit model parameters will be presented for SPR West Hackberry and Bryan Mound caverns. As examples, pressure data from a cavern from each site, will be compared to predicted model pressures.

Salt Creep Model

The creep of salt was represented by the multi-mechanism deformation (M-D) model (Munson, Fossum, and Senseny, 1989a,b). The model is state-of-art in predicting time-dependent salt deformation and is based on a first principles approach. The model was originally developed by Munson and Dawson (1979, 1982) and later modified to provide a more descriptive transient strain function (Munson, Fossum, and Senseny, 1989a,b). Transient creep is incorporated through both workhardening and recovery branches that reflect the internal structure in the salt (Munson and Dawson, 1982). When salt is developing internal structure it is workhardening and hence developing a resistance to creep. As a result, the strain rates decelerate over time. Conversely, a recovery mode in salt is manifested by accelerating strain rates. At equilibrium, the salt is in steady state creep.

The M-D model has several steady state creep mechanisms, of which only one (mechanism 2) was selected for use in the cavern model based on its dominant influence over the other mechanisms for SPR caverns. The dominance of a mechanism is determined by stress and temperature regime for the cavern. For this mechanism the steady state creep rate is

$$\dot{\varepsilon}_s = A\, e^{-Q/RT} (\sigma / \mu)^n$$

The above mechanism relates the steady state strain rate to temperature, T, and stress, σ. The constants A, n, Q can be determined from laboratory creep tests, where Q is the activation energy and n is the stress exponent. R is the universal gas constant and μ is the shear modulus of salt.

Transient creep is included in the model through a function, F where the total strain rate (transient and steady state) is the product of F times the steady state strain rate.

$$\dot{\varepsilon} = F \dot{\varepsilon}_s$$

The transient function, F, is composed of a workhardening, equilibrium, and recovery branches. F is greater than 1 when the salt is workhardening, and F is less than 1 when the salt is in a recovery mode. When F is equal to one, there is no transient effect.

$$F = \begin{cases} e^{\Delta(1-V/e_t)^2} & , V < e_t \text{ Workhardening} \\ 1 & , V = e_t \text{ Equilibrium} \\ e^{-d(1-V/e_t)^2} & , V > e_t \text{ Recovery} \end{cases}$$

Δ and δ are workhardening and recovery parameters, and e_t is the transient strain limit. The internal state variable, ζ, is compared to the transient strain limit to determine whether the salt is in equilibrium or is workhardening or recovering. The equation governing the evolution or rate of change of the internal variable, is

$$\dot{z} = (F - 1)\,\dot{e}_s$$

The transient strain limit is related to stress and temperature through the following function where K_0, c, and m are constants.

$$e_t = K_0\, e^{cT} (s / m)^m$$

The workhardening and recovery parameters are defined as a function of stress through

$$\Delta = a_w + b_w \log(s / m)$$
$$d = a_r + b_r \log(s / m)$$

where the α's and ß's are constants with the subscripts denoting either the workhardening or recovery branches.

The relevant creep parameters are only partially know for SPR domal salts. Significant variability is known to exist among measured laboratory creep of salts from the same dome and from dome to dome (Wawersik and Zeuch, 1984). The complete set of creep properties have been measured for low impurity (clean) salt from the Waste isolation Pilot Plant (WIPP) site (Munson, Fossum, and Senseny, 1989a,b). This salt (Table 1) is assumed to represent the relatively pure quality found in domal salts.

The creep equations can describe the time-dependent strain rate of salt subject to a given stress state. The stress state around a cavern varies both spatially and with time. Typically, the finite element method which traces the spatial and time variation of stress is used to predict cavern volume changes, and hence pressurization over time. However, this approach is computationally intensive. In the absence of these analyses, the following engineering approach was adopted.

An approximation of the stress state and the amount of salt being stressed was used to calculate a representative cavern closure rate. Here, the deviatoric stress or differences in the principal stress magnitudes control creep. The deviatoric stress is assumed to be proportional to the difference in lithostatic and oil pressure acting against the cavern wall. However, the deviatoric stress state that controls creep is unknown. To account for this, a factor, f, was incorporated into the following equation. This factor reflects the triaxial stress state of the salt. The deviatoric stress used in predicting cavern pressurization is defined as:

$$s = (1 - f)(P_L - P_d)$$

where P_d is defined as the oil pressure at depth acting against the cavern wall and P_L is the lithostatic pressure. Lithostatic pressure is influenced by depth, the caverns in a field, and other factors, therefore it is considered an unknown and is optimized to find a value that best fits the data. Similarly, the true triaxial stress state of the salt surrounding a cavern is unknown and f is also optimized to best fit measured cavern pressures.

The amount of salt subject to creep was defined as length parameter, L in the model. It represents the distance from the cavern wall into the salt that is stressed. The characteristic length parameter is also unknown and optimized to best fit previous cavern pressure data. Knowing the strain rate from the above equations and stress state, and the characteristic length of salt, the change in cavern diameter can be calculated as:

$$\Delta D = \dot{e}\, L \Delta t$$

where Δt represents a time step in the model. The volumetric change for a cylindrical cavern follows as:

$$\Delta V = (p\ /\ 4)\Delta D(2D_o - \Delta D)H$$

where D_o is the initial cavern diameter and H is the cavern height. The pressurization due to creep is then calculated as:

$$\Delta P = K\frac{\Delta V}{V}$$

where K is the compressibility of the fluid in the cavern and V is the volume of the cavern.

In addition to the stress state and volume of salt stressed, an initial value is needed for the internal variable used to calculate transient creep. The variable reflects the internal microstructure in the salt that has accumulated over time since the beginning of leaching. Since this parameter evolves with time and complete cavern pressure histories are not available, it is impossible to simulate its development to date. Therefore, the initial value of the state parameter for a given data set is a free variable in the model that also can be optimized to best fit the historic pressure data.

In summary, four creep related parameters were selected for optimization. The lithostatic stress, the triaxial stress factor, the characteristic length, and the initial internal variable. The remaining parameters used in the model are listed in Table 2.

Thermal Model

An estimate of the temperature rise of a fluid filled cavern is made by assuming that the primary limitation to heat transfer is the thermal conductivity of salt. The fluid in a cavern is predicted to be well mixed (Tomasko, 1985 and Webb, 1988) and the observed temperatures are known to be nearly isothermal (Mills, 1993). This thermal conduction problem has been described by Carslaw and Jaeger (1959) and they give an analytical solution to the equation in cylindrical coordinates.

The equations describing the temperature rise of cavern fluids are:

$$T = T_o + (T_\infty - T_o)G(a, \frac{kt}{r^2}),$$

where

$$G(a, \frac{kt}{r^2}) = 1 - \frac{4a}{p^2}\int_0^\infty \frac{\exp\left(-ktu^2 / r^2\right)du}{u\left\{\left[uJ_0(u) - aJ_1(u)\right]^2 + \left[uY_0(u) - aY_1(u)\right]^2\right\}}.$$

In the above equations T_∞ is the ultimate undisturbed mean cavern temperature, T_o is the initial cavern temperature, κ is the thermal diffusivity of the salt, r_{cav} is the cavern radius, J_0, J_1, Y_0, and Y_1 are Bessel functions. α is a parameter equal to twice the ratio of the heat capacity of an equivalent volume of salt to that of the fluid filled cavern.

The determination of the proper initial time in the above equations requires a heat balance of the leaching process. The endothermic heat of dissolution was found to almost exactly balance the heat capacity of the relatively warm dissolved salt so that the temperature of the brine in the cavern was very approximately equal to the temperature of the leach water during cavern formation. It was further discovered that the rate of cavern formation was approximately equal to the rate that the thermal front progresses into the salt. The effect of these processes is that the temperature of the salt face at the conclusion of leaching is approximately equal to that of the undisturbed salt. Therefore, the initial temperature of the cavern fluids is approximately equal to the temperature of the input water used for leaching. Additionally, the salt temperature is not significantly changed by the leaching process so the initial thermal driving force is defined by the undisturbed salt temperature and the initial cavern temperature. Because of this, time is measured from the conclusion of leaching.

The parameter, α, may take on values between 0.94 and 2.2, depending on whether the cavern is water or oil filled. The shape of the temperature history curves is almost completely insensitive to the values of α, given that the value of the thermal diffusivity may be adjusted to give the best fit of the data. Because of the insensitivity of the model fit to the value of α, its value was arbitrarily set to 1.33, a reasonable value within the possible range of values.

The solution to the above equations requires numerical integration. However, it is also possible to use the following approximation which was developed and is sufficiently accurate (Ostensen, 1995b) for this purpose.

$$G(t^*) = \frac{1.224 t^{*0.47}}{\left(1 + (1.224 t^{*0.47})^{1/0.54}\right)^{0.54}},$$

where

$$t^* = \frac{kt}{r^2},$$

and α is assumed to be 1.33 as before. The model requires the rate of change of cavern temperature. The rate of temperature rise of the cavern is defined by

$$\frac{dT}{dt} = \left(T_\infty - T_o\right)\frac{4ak}{p^2 r^2} F\left(t^*\right)$$

where

$$F(t^*) = \int_0^\infty u \frac{\exp\left(-t^* u^2\right) du}{\left\{\left[uJ_0(u) - aJ_1(u)\right]^2 + \left[uY_0(u) - aY_1(u)\right]^2\right\}},$$

and F(t*) may be approximated by

$$F(t^*) = \frac{0.968}{t^{*0.55}\left(1 + 2.522t^*\right)}.$$

The solution of the numerical model is thus a function of the initial cavern temperature at the conclusion of the leaching phase, the ultimate undisturbed mean cavern temperature, and the thermal diffusivity of the salt. Values of these are given in Hinkebein (1995a,b).

Parameter Optimization

To achieve the best possible fit between the historical cavern pressure data and the cavern pressures calculated with the model, the creep and thermal parameters were separately evaluated.

Optimization of the thermal model required varying only the thermal diffusivity of each cavern to best match the thermal model predictions to previously measured cavern temperatures. For the creep model, the characteristic length of the salt, the lithostatic stress, the triaxial stress factor, and the initial internal variable were optimized. Optimization using additional parameters never produced superior results, probably because all the other parameters are correlated in some way to these four parameters.

The optimization scheme used is the SIMPLEX algorithm developed by Caceci and Cacheris (1984). As input, the scheme requires a subroutine which computes the cavern pressure at all times, as a function of the model parameters which are to be optimized, and starting guesses for the model parameters. The algorithm systematically varies the model parameters in such a way as to minimize the root mean square difference between the calculated and measured data. The root mean square difference, D_{rms}, is defined as

$$D_{rms} = \sqrt{\frac{\sum (P_{data} - P_{model})^2}{N - 1}}$$

where P_{data} and P_{model} are the measured and calculated values and N is the number of daily pressure measurements used in the analysis. Erroneous pressure data and pressures artificially manipulated by cavern operations were excluded from the above calculations.

D_{rms} has units of pressure and can be likened to a standard deviation. If the model and data differ by less than twice D_{rms}, then one can assume with 95% confidence that the data and the model agree.

RESULTS

Two of the SPR caverns, West Hackberry Cavern 102 and Bryan Mound Cavern 110, were selected to demonstrate the predictive capabilities of the model. The West Hackberry cavern represents a relatively poor fit to the model, whereas the Bryan Mound cavern represents a relatively good fit.

The results of the optimization operations are tabulated in Table 3. The optimized values for the thermal and creep models are listed. The optimized parameters exhibit quite a bit of variation among caverns, but for the most part fall within reasonable ranges. In many cases where a particular parameter falls outside of the expected range, a more realistic set of values for the cavern could have been obtained with only a slight sacrifice in error.

Figures 1 and 2 show the thermal model fit to temperature data from West Hackberry Cavern 102 and Bryan Mound Cavern 110. The geothermal heating of cavern fluid accounts for roughly one-tenth and one-third of the total cavern pressure for West Hackberry and Bryan Mound, respectively. The differences in pressurization attributed to geothermal heating vs. creep are due in part to the measured creep rates of salt at those sites. West Hackberry salt creeps at a much faster rate than Bryan Mound salt (Wawersik and Zeuch, 1984).

The error values (D_{rms}) range from a low of 4.4 psi to a high of 13.0 psi with an average of 8.2 psi. This is quite small compared to the typical 700 to 900 psi operating pressure of the caverns. Given that the resolution of the manual pressure readings used to constrain optimization is 5 psi, these results are very good. To illustrate the excellent match between the data and the model, example plots are provided for West Hackberry 102 and Bryan Mound 110. Figures 3 through 6 show both the measured and calculated cavern pressure and the difference between these values as a function of time for the two caverns. The results indicate that the model did an excellent job of matching the data. Since the predicted model pressures monotonically increase with time, the scatter presented in Figures 4 and 6 represent that due to the data collected.

The D_{rms} values in Table 3 permit a first estimate of the minimum detectable leak size to be made. For example, a cavern with a D_{rms} value of 10 psi, the minimum pressure drop that could be attributed with 95% confidence to a leak would be 20 psi. Using a typical cavern compressibility of 50 bbl/psi, this would mean a leak of about a 1000 bbl. The other means of detecting a leak is to graphically compare the discrepancy between the measured and predicted pressure to all previous data and model results. Given the resolution of the data, leak evaluation should be made at the end of a pressure cycle, unless gross discrepancies are observed. Leaks larger than minimum detectable will be discernible within shorter time periods. Regardless of the time period evaluated, if a discrepancy is greater than anything observed to date, there is cause for concern.

The typical duration of a pressure cycle at West Hackberry is 3 to 6 months. The slower creeping salt a Bryan Mound requires cavern pressures to be bled much less frequently, typically after 6 to 12 months. Following a pressure change, the predicted cavern pressure is set to match the first daily pressure measurement made. The D_{rms} at that time is zero. For the previous pressure cycles at West Hackberry and Bryan Mound, the average D_{rms} is 9.1 and 7.1 psi, respectively. Therefore, the minimum detectable leak is estimated at 910 and 710 bbl, respectively. Given the differences in the typical duration of the pressure cycles, the minimum detectable leak rates are calculated as 2400 bbl/yr for West Hackberry and 940 bbl/yr for Bryan Mound caverns. Leak rates exceeding these amounts would be detected within the duration of the typical cavern pressure cycles. Since the performance of the model varies with individual caverns, as do typical durations of pressure cycles, the detectable leak size and rate will also vary by cavern.

Figure 3 provides an example of a potential leak. Notice that in the Fall of 1990, the pressure data dropped noticeably below the model predictions. This was a negative 30 psi discrepancy or a potential 1500 bbl leak. Discrepancies of this size are readily noticeable and fast corrective action can be taken. In this case, the pressure drop in West Hackberry 102 was not due to underground leakage, but the result of a surface valve. Less subtle, are gradual pressure drops which slowly develop over time. To detect these, a cavern pressure model and accurate data are required. An improved pressure monitoring system is planned for SPR sites that will allow for better model calibrations in the future, and even faster and smaller leak detection.

CONCLUSION

A model has been developed that accurately predicts the well head pressure of SPR caverns at Bryan Mound and West Hackberry. The model accounts for cavern pressurization due to creep and geothermal heating of the oil. Each cavern was custom fitted with parameters that result in a best fit to the previous five years of cavern pressure data collected. The model can detect a loss of less than 0.01 percent of the cavern inventory over a typical pressure cycle.

The model is adaptable to any fluid filled cavern in salt. The process requires previous pressure data, and thermal data, if available. Selected parameters are then optimized to best predict cavern pressures. An optimization tool and the model are available on an Excel spreadsheet for use on a personal computer.

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Table 1. Mechanical Properties of Low Impurity Salt

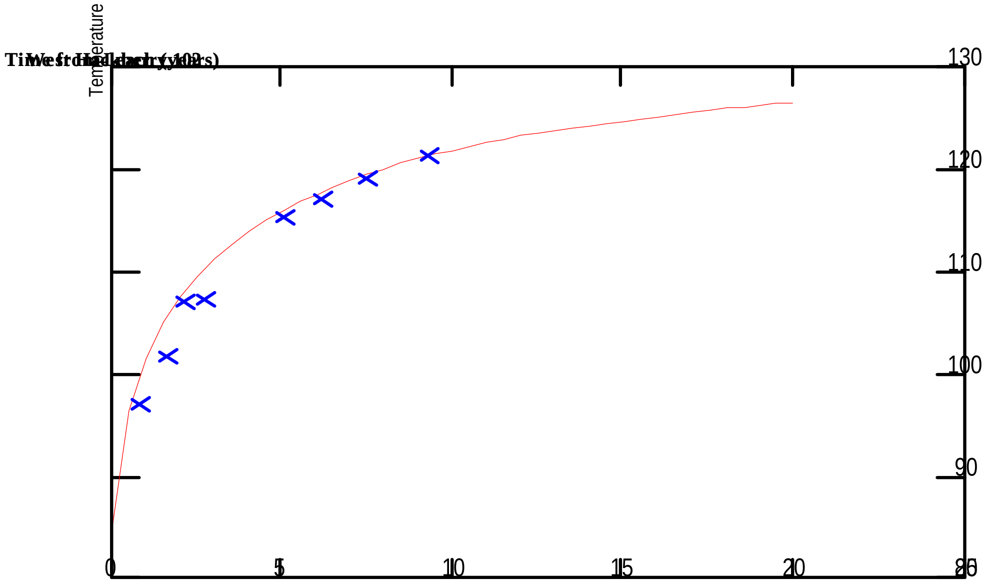
Steady State Creep		Transient Creep	
A	9.672 E12 /s	m	3.0
Q	12000 cal/mol	K_0	6.275 E5
n	5.0	c	0.009198 /T
		α_w	-17.37
μ	1.8×10^6 psi	$ß_w$	-7.738
R	1.987 cal/mol-deg	α_r	-3.0
		$ß_r$	-1.1

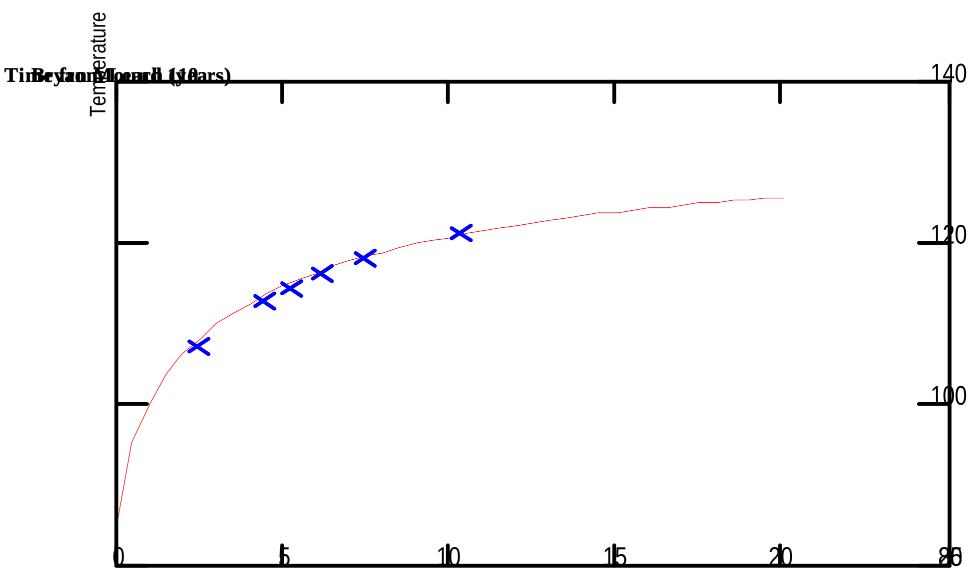
Table 2. Model Parameters

Oil Properties	West Hackberry 102	Bryan Mound 110
API (deg)	37.6	32.8
Volume (MMB)	10.43	10.22
Initial Temperature (F)	80	80
Cavern Properties		
Depth to Roof (ft)	2628	2150
Depth to Bottom (ft)	4502	4118
Total Volume (MMB)	11.10	11.46
Well Head Pressure (psi)	901	688
Leach Date	11-8-84	12-23-82
Salt Temperature (F)	130	130

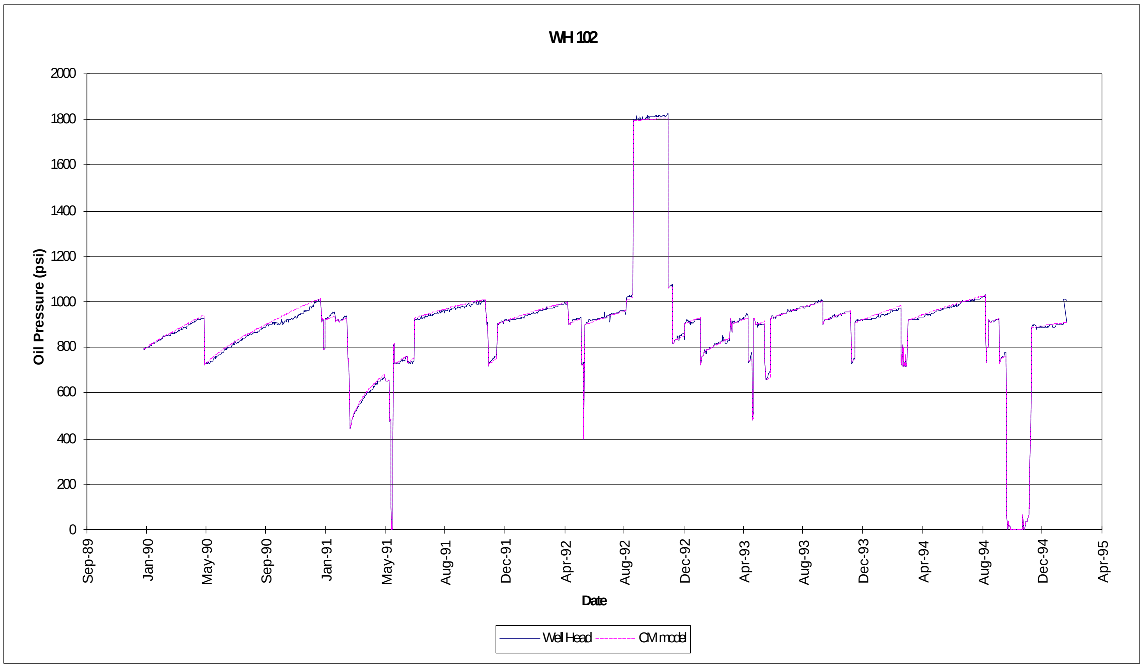
Table 3. Results of Optimization Exercises

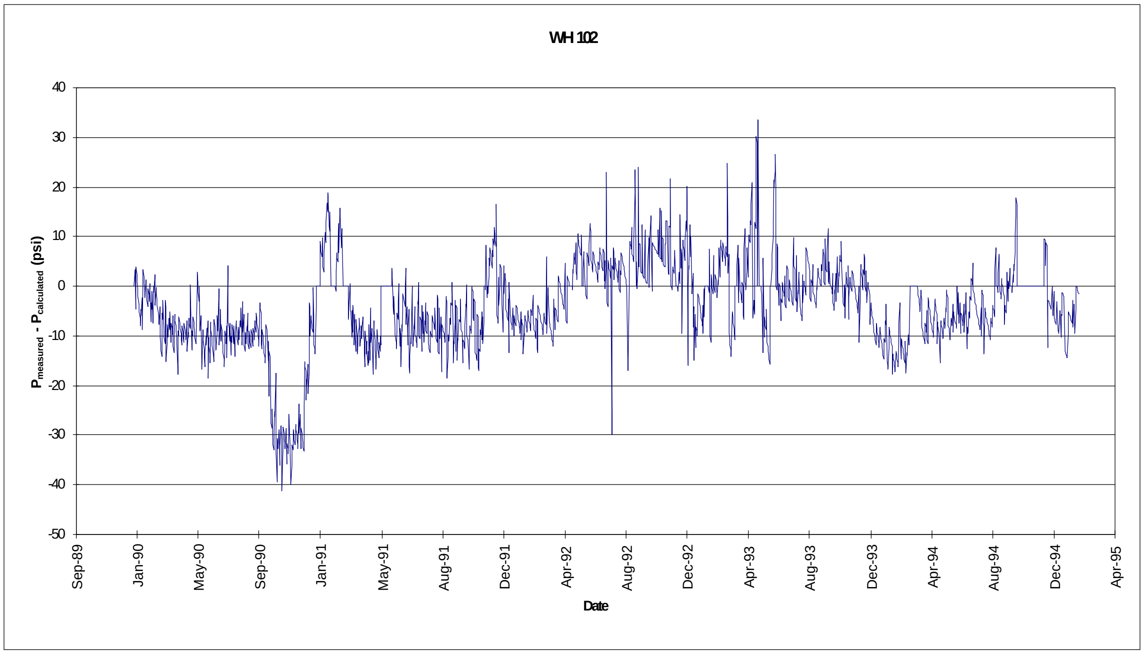
Cavern	Diffusivity / r_{cav}^2 (1/yr)	Salt Stress (psi)	Triaxial Stress Factor	Char. Length (ft)	Internal Variable (31-Jan-95)	D_{rms} (psi)
WH101	0.136	3957	0.10	8.53	0.019376	8.5
WH102	0.118	4189.5	0.63	327	0.001589	11.9
WH103	0.112	4329	0.61	138	0.002332	7.9
WH104	0.112	5324	0.78	406	0.001029	7.7
WH105	0.123	4238	0.34	19.75	0.005290	9.4
WH106	0.105	4226	0.26	10.4	0.008625	7.9
WH107	0.112	4223	0.18	9.04	0.010509	9.1
WH108	0.105	4719	0.40	8.58	0.010518	8.9
WH109	0.11	5118	0.74	308	0.001219	8.5
WH110	0.065	4756	0.72	498	0.000864	8.3
WH111	0.08	5180	0.75	285	0.001087	8.5
WH112	0.099	4746	0.68	264	0.001306	13.0
WH113	0.078	5467	0.75	258	0.001679	10.6
WH114	0.12	5030	0.75	438	0.000911	9.7
WH115	0.078	5102	0.76	464	0.000831	6.9
WH116	0.105	4523	0.51	72.65	0.005293	10.1
WH117	0.078	4780	0.65	171	0.001894	12.1
WH6	0.037	4995	0.72	442	0.001466	11.9
WH7	0.032	4842	0.73	393	0.001578	7.0
WH8	0.06	3909	0.66	490	0.000984	8.4
WH9	0.039	3850	0.45	202	0.004976	7.4
WH11	0.067	4186	0.67	292	0.001016	6.7
BM101	0.108	4832	0.84	379	0.000238	6.9
BM102	0.121	3560	0.69	486	0.000345	6.0
BM103	0.103	4007	0.64	134	0.001009	8.6
BM104	0.086	3457	0.49	53.7	0.001757	7.0
BM105	0.08	4006.5	0.42	4.82	0.003700	5.8
BM106	0.108	4773	0.81	372.5	0.000446	4.4
BM107	0.088	3825	0.69	262	0.000675	6.5
BM108	0.101	3452	0.58	246	0.000885	7.0
BM109	0.101	3510	0.50	112	0.001116	7.5
BM110	0.101	3418	0.31	10.4	0.002349	4.5
BM111	0.073	3647	0.34	4.88	0.003604	5.9
BM112	0.118	3601	0.61	270	0.000894	7.7
BM113	0.187	5418	0.61	7.935	0.006025	9.6
BM114	0.157	5464	0.79	280	0.001083	10.7
BM115	0.118	3785	0.39	39.5	0.003608	9.7
BM116	0.11	5485	0.86	851	0.000351	6.0
BM1	0.052	3977	0.81	372	0.000271	6.1
BM2	0.09	2206	0.77	441	0.001073	12.1
BM4	0.016	3242	0.54	170	0.001257	4.5
BM5	0.014	3716	0.67	133	0.000988	5.4



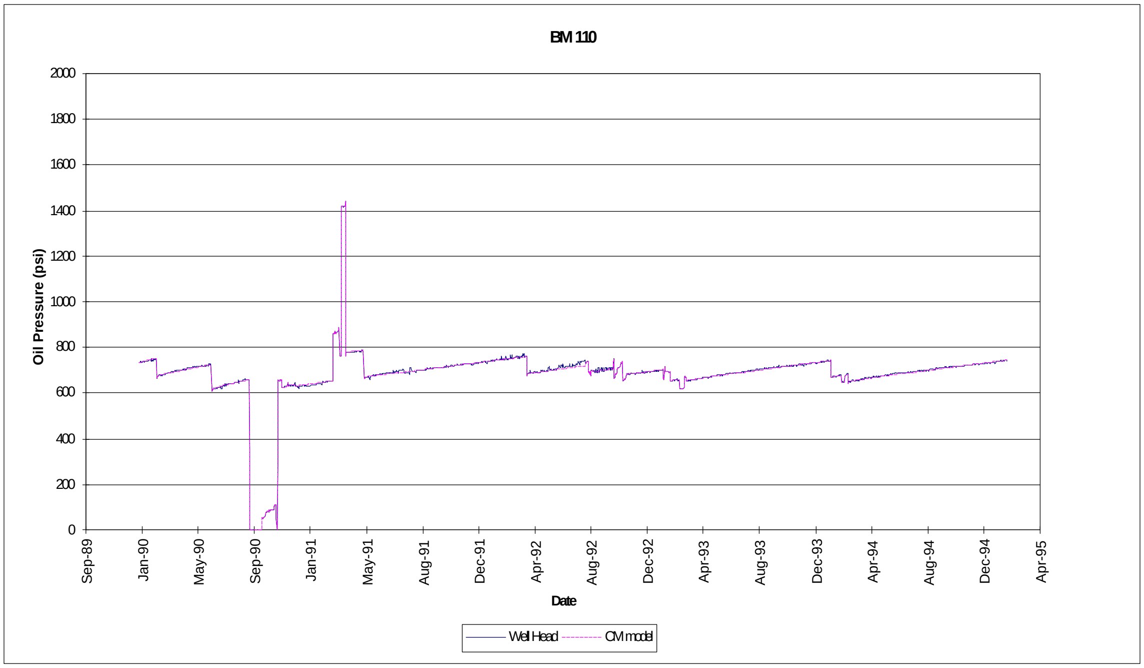


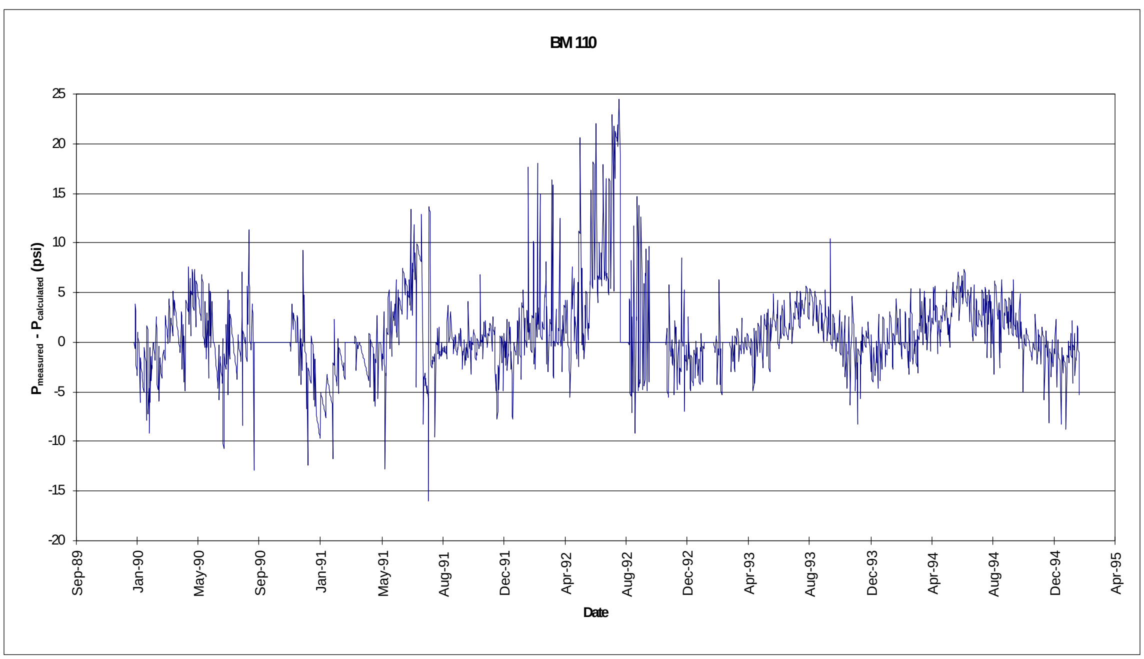
Figures 1 and 2. Comparison of thermal model to oil temperature data for for West Hackberry Cavern 102 and Bryan Mound Cavern 110.





Figures 3 and 4. Comparison of pressure data and model predictions for West Hackberry Cavern 102.





Figures 5 and 6. Comparison of pressure data and model predictions for Bryan Mound Cavern 110.